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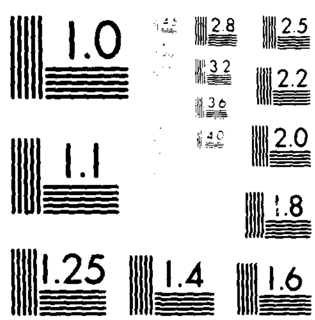

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THESIS

EVALUATION OF CALIBRATION METHODS FOR
HYDROGRAPHIC ELECTRONIC POSITIONING SYSTEMS

by

Kenneth Wingo Perrin

September 1980

Thesis Advisor: D. E. Nortrup

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Evaluation of Calibration Methods for Hydrographic Electronic Positioning Systems

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The accuracy requirement for hydrographic positioning systems and the types of systems used are identified. The nature of the position accuracy and sources of errors in the determination of a position are defined.

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I. INTRODUCTION

A. ACCURACY OF POSITIONING

The accurate positioning of a sounding vessel is a fundamental element of hydrographic surveying. According to the International Hydrographic Bureau (IHB), the required accuracy for positioning, combined with the allowable plotting error, is one and a half millimeters at the scale of the survey [Ref. 1]. The minimum plotting error is approximately two-hundredths of an inch or one-half millimeter [Ref. 2]; therefore, the position accuracy itself must be one millimeter or better. For example, at a survey scale of 1:10000, one millimeter equates to a position accuracy of ten meters.

1. Blunders, Random, and Systematic Errors

Blunders, random, and systematic errors affect the accuracy of an electronic positioning system.

Blunders are mistakes which result from misreading instruments, transposing figures, faulty computations, etc. They are usually large and easily detected through repeated measurements and can be eliminated by manual or automatic data evaluation routines, either on or off line.

Random errors are unpredictable in magnitude and direction and are governed by the laws of probability. They may derive from instrument errors, observational errors, ephemeral propagation anomalies, e.g., anomalies due to lightning, etc.

The random error of any measurement system can be evaluated by making repeated measurements of the same quantity, e.g., measurement of a fixed range with a positioning system. The computed standard deviation of these measurements may be used as an estimate of the random error for that system. The standard deviation will vary from one positioning system to another. For example, as determined by the manufacturer, Del Norte Transponder has a σ of plus or minus three meters per line-of-position (lop), while Argo has a σ of plus or minus ten meters per lop (average installation [Ref. 3]. The random errors of the electronic positioning system must be statistically quantified to determine if the system meets the accuracy requirements, that is, whether the positioning system is of hydrographic quality or not.

Systematic errors follow some law by which they can be modeled. Accuracy of determining the model depends upon the accuracy by which the governing law is derived [Ref. 4]. These errors occur in a predictable direction and induce a shift or bias into an observation. If, for example, the mean observed coordinates at a given point differ from the computed value for that point and the differences remain unaltered with time, a systematic error exists. The errors may be caused by built-in instrument bias (fixed error), observer bias, errors from predicted refraction (variable error), errors from radio waves, i.e., changes in the velocity over the propagation path, etc.

The better the systematic errors are identified and modeled, the better the achievable accuracy of the electronic positioning system. The errors must be modeled so they can be removed either by instrument adjustment or by correcting position data. Unfortunately, all systematic errors cannot be modeled and removed. A calibration provides a means of estimating residual systematic errors. A calibration is the comparison of the positioning system's indicated range or position and a "known" range or position. From this comparison the total effect of all remaining systematic errors is estimated. Correctors are then applied to the data or adjustments are made to the surveying system in order to compensate for these remaining systematic errors.

Refraction and radio wave velocity are the most difficult systematic error sources to model. Refraction is affected by temperature, atmospheric pressure, and humidity. It is directly related to the frequency of the electronic positioning system, varying within the light spectrum, but being almost constant within the radio band except near 60 GHz and around 22 GHz where there is dispersion similar to that of light emission [Ref. 5].

Propagation velocity of radio waves is affected by the conductivity of water and ground surfaces. Velocities may vary from 299,670 kilometers per second over sea water to 298,800 kilometers per second over rocky mountainous land.

An example of a systematic error resulting from the use of an incorrect propagation velocity is that of a radio wave velocity of 299,670 kilometers per second being utilized when the actual velocity of propagation is 299,370 kilometers per second. An error of 300 kilometers per second would exist in the determination of each line-of-position. Thus, a range measurement based on a travel time of 10^{-5} seconds would result in a difference of three meters at three kilometers, i.e., one meter per kilometer.

Refraction and radio wave velocity, the major sources of systematic error, affect the electronic positioning system lattice making the actual lattice different from an ideal lattice of the system (see Figure 1).

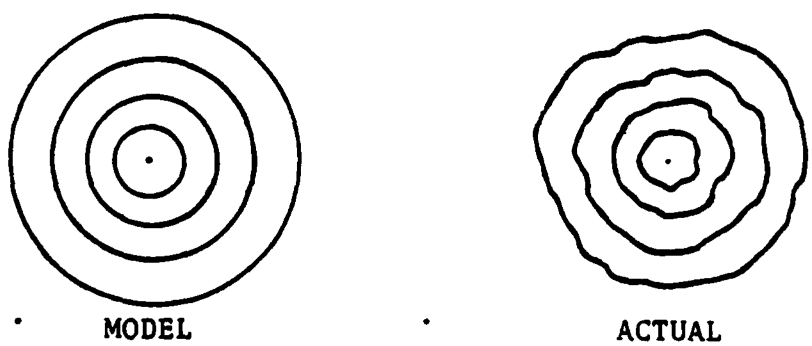

Figure 1. Propagation velocity spatial pattern.

A constant value for propagation velocity of radio waves is used in constructing hyperbolic or circular lattices. These smooth lops are idealized mathematical models of the actual lattice. As a result of the spatial and temporal variability of refraction and propagation velocity, each is an irregular and undetermined surface as shown in Figure 1.

2. Repeatability and Predictability

The accuracy of an electronic positioning system is a function of two terms, "repeatability" and "predictability."

"Repeatability" is the measure of the relative accuracy with which the system is able to return to a specific point defined in terms of its lattice, i.e., electronic lines-of-position [Ref. 6]. Repeatability is a function of the random and systematic errors of the system and the angle at which the lops intersect, i.e., the net geometry of the system. For a hyperbolic system, the net geometry is also affected by the expansion factor of the lattice.

Random errors and the net geometry are included in the root mean square (drms) error measure of repeatability. Root mean square is a function of the standard deviation in each measurement (line-of-position) contributing to a position determination. Root mean square error can be expressed by the following equation for ranging systems:

$$\text{drms} = \sqrt{\sigma_1^2 + \sigma_2^2} \quad \csc \beta$$

in which, β is the angle of intersection of two lines-of-position, σ_1 and σ_2 are the standard deviation of each lop measurement in distance units [Ref. 7]. The drms equation assumes that there is a normal distribution of random errors. Position accuracy can be stated in terms of the computed drms value since it can be shown that 63.2% to 68.3% of the time a survey position will fall within a circle with a radius of one drms. The exact percentage is a function of the angle β. When β = 90 degrees, the percentage is 63.2%. As the angle of intersection approaches zero, the computed drms value converges to a 68.3% interval [Ref. 8]. Usually, the standard deviation for both lines-of-position is taken as being the same for a particular positioning system, that is $\sigma_1 = \sigma_2$. Thus, the accuracy of any positioning system is a function of the standard deviation and the net geometry. For example, let

$$\sigma_1 = \sigma_2 = \pm 3 \text{ meters}$$

$$\beta = 90^\circ$$

Then, $\quad \text{drms} = \sqrt{3^2 + 3^2}\,\csc 90^\circ = 4.2 \text{ meters}$

For $\beta = 45^\circ$, drms = 6.0 meters.

"Predictability" is the measure of the absolute accuracy with which the electronic positioning system can define a point's location in terms of geographic coordinates rather than the system's electronic coordinates [Ref. 6].

It requires that all systematic errors have been corrected and only random errors remain. Unfortunately, in hydrographic surveys, all systematic errors cannot be modeled and removed. However, through calibration, these errors can be accurately estimated so that adjustments may be made to the electronic instruments or the data. The more extensive the calibration, the better systematic errors will be estimated and, thus, the more accurate the determination of random errors.

B. CALIBRATION OF ELECTRONIC POSITIONING SYSTEMS

A calibration is a comparison of an electronic positioning system's range or position to an independently determined known range or position. Generally, the calibration data is applied when the errors are greater than the σ of the positioning system. The navigator unit aboard the vessel may be adjusted to read the correct rates or correctors may be applied to all position data.

To obtain optimum results, calibrations should be provided continuously, obtaining precise information at all ranges, in all weather, 24 hours a day, for correlation with environmental data acquired concurrently. A continuous calibration record is needed throughout the entire survey area to establish a model of all systematic errors in the system's performance over time and distance.

Since such optimum calibration results cannot be obtained, a compromise must be made as to when, where, and how to calibrate. Calibrations should be made at such a frequency and over various areas of the survey to ensure the accuracy of the positioning system. By determining instrument bias and modeling, or at least measuring, systematic errors at various points throughout the survey area, a calibration relates the electronic positioning system's actual lattice to the geographic coordinates.

II. NATURE OF PROBLEM

A. ELECTRONIC POSITIONING SYSTEMS

1. Position Accuracy

The International Hydrographic Bureau's standard for positioning accuracy, presented in the introduction, is open to interpretation. The statement, "seldom to exceed one and a half millimeters at the scale of the survey" [Ref. 1] does not specify how much of the tolerable error must be reserved to accommodate plotting inaccuracies. Each survey organization must choose a standard measure of error (circular error, root mean square error, or some other measure) and quantify the level of acceptability for position accuracy. The National Ocean Survey of the National Oceanic and Atmospheric Administration (NOAA) for example, in applying the IHB accuracy standard, uses the root mean square error and has established one-half millimeter at the scale of the survey as the allowable inaccuracies inherent in the position measurement system. Thus, for a survey at a scale of 1:10000, this standard requires a positioning accuracy of five meters [Ref. 7].

2. Hydrographic Positioning Systems

The established accuracy requirement is achieved by the proper use of hydrographic quality survey system. These systems fall into two primary categories: pulse signal-elapsed time systems and continuous wave-phase comparison systems.

Pulse signal-elapsed time systems measure the transit time of a radio pulse between a transceiver and a transponder unit. Time is converted to an accurate distance based on the velocity of propagation of electromagnetic radiation. These systems can operate in either a range measurement mode, where transit time is measured between two stations, or in the hyperbolic mode where the difference in range from a vessel to two known points is determined.

Continuous wave-phase comparison systems measure the difference in phase of the two-path signal. Position is determined relative to lines of zero-phase difference. This system can operate in either the range or hyperbolic measurement mode.

For a comprehensive discussion of these principles, consult the IHB's Special Publication No. 39 [Ref. 9].

B. ACCURACY REQUIREMENTS AND CALIBRATION OF POSITIONING SYSTEMS

A survey unit's main objective is to obtain hydrographic data. Therefore, it is not possible or practical to calibrate an electronic positioning system as often and in as many locations of the survey area as would be necessary to completely model the systematic errors throughout.

Calibrations are usually performed at the beginning and end of a survey to determine any correctors and adjustments to the system. Daily or twice-daily calibration checks are made on a positioning system in the survey area to monitor any variations.

A careful calibration must be made since any error in a calibration will induce an additional systematic error in survey data until the next calibration is performed. The accuracy of a calibration is solely a function of the accuracy of the determination of the known rates, ranges, or positions used for comparison. The calibration method used must be more accurate, preferably an order of magnitude more accurate, than the accuracy of the electronic positioning system being checked. Each calibration procedure should consist of a minimum of two independent observations. The National Ocean Survey, for example, requires that the correctors for each successive comparison must agree to within one-half millimeter or ten meters at the scale of the survey, whichever is less [Ref. 10].

III. PURPOSE FOR RESEARCH

There are a variety of techniques by which an electronic positioning system can be calibrated. A particular method utilized by an individual field unit may be a matter of habit rather than a knowledgable choice based on the positioning system and operating circumstances. The methods that are frequently used are often inefficient and less accurate than desirable. This is due in part to an absence of appreciation for the wide variety of available calibration methods.

The object of this research is to alleviate the above condition by making available an inventory of methods for calibration and their associated attributes. Through the application of appropriate calibration methods, an increased operating efficiency and product quality should be achieved.

IV. RESEARCH PROCEDURE

In order to supplement published methods of calibration, a questionnaire was sent to people currently involved in hydrographic survey work requesting information as to the various calibration techniques being presently employed. The questionnaire was also sent to the manufacturers of hydrographic positioning systems. The questionnaire asked for the type of positioning system being used, what procedure(s) was employed to calibrate the system, and the estimated accuracy of each calibration method [Appendix A].

The response was very good. Of the 30 questionnaires sent, there were 21 acknowledgements, equating a 70% response rate. All those answering requested copies of this report, indicating a desire for this type of information.

V. CALIBRATION METHODS

Calibration methods can be grouped into three general categories: range-comparison, position comparison, and auto-calibration. The nature of range-comparison is to compare a known distance to the range as measured by a positioning system (stationary calibration). The position-comparison involves comparing the lattice coordinates of a known position to the rate indicated by the positioning system at that location (stationary or dynamic calibration). The nature of auto-calibration is to calibrate an electronic positioning system by the use of redundant lop information (dynamic calibration).

A. RANGE-COMPARISON METHODS

The range-comparison method is based on the comparison of a known distance to an electronic positioning system's range measurement between the same end points. This procedure is applicable to either pulse-time or phase-comparison systems operating in the range measurement mode. For microwave systems, calibration measurements can be made over either land or sater since the propagation velocity is unaffected by surface conductivity. With lower frequency systems, the calibration should be made over water since the propagation velocity of radio waves is affected by conductivity of the surface over which it travels.

When calibrating positioning systems that operate in the microwave frequency range, special care must be taken to avoid errors due to multipath and grazing angle effects [Ref. 11].

The range-comparison method requires a clear line-of-sight so as to avoid interference of the transmitted signal. Direct comparisons are made between the electronic positioning system's range readings and the actual distance. This procedure can be done ashore, which allows redundant observations, or at sea. Several readings should be made to obtain a mean value, i.e., reduce the effects of random errors, before determining if any adjustments to the positioning system or corrections, to be applied to previous positions, are necessary

Each range measurement of the positioning system, when compared to a known distance, provides an estimate of the systematic errors affecting the system. These errors will show up as differences between the positioning system range and the known distance for that particular propagation path.

1. Base-Line Method

The base-line method involves the comparison of an electronic positioning system's range measurement of a known precomputed or measured distance. This "known" range can be either an inverse distance (precomputed) between two horizontal control stations of at least third-order accuracy, or a length measured, with a surveying quality electronic distance measuring (EDM) instrument (measured), between two points. The base line is the known distance in this context and the term "base-line" should not be confused with that line connecting two control stations in a hydrographic survey net.

The remote antenna unit of the positioning system is centered over the established point at one end of the base line and a master antenna unit and navigator at the other end; observations and comparisons are made. With this basic set-up no temporal or spatial variations are considered. In order to account for the spatial variations, two approaches may be taken: (1) use of in-line audio attenuators, or (2) set up different length base lines.

a. Base-Line Comparison with Attenuators

Variable ranges may be simulated by utilizing a variable in-line audio attenuator on a positioning system. Since signal strength decreases with increasing range, calibration of the positioning system over a variety of ranges (simulated) can be accomplished by using different size dB attenuators such that the signal strength is reduced. This allows the limiting signal strength values for maximum ranges to be determined. Calibration can be completed on a single set-up, with no need to establish different base-line distances.

b. Base-Line Comparison without Attenuators

Base-line distances should be approximately equal to the maximum range over which the positioning system will be used. Comparisons should be made at different ranges between the minimum and maximum survey distances in order to determine spatial variations over the total range. This procedure requires separate set-ups for each range comparison.

When performing these comparisons, with or without attenuators, signal strength should be monitored to determine the maximum distance for which accurate range information can be received.

The temporal variation of the positioning system can be estimated by performing the comparisons over a long period of time and at different times during the day (morning and evening). The σ of the observations may be determined if a large enough data set is collected.

The expected accuracy of the base-line method, if the known distance is determined by using two geodetic control points of at least third-order accuracy, is on the order of one part in 10,000. Measuring the base line several times with an electronic distance measuring instrument should provide an accuracy of plus or minus one millimeter to plus or minus five centimeters, depending on the make and model of the EDM instrument used [Ref. 12]. The repeatability of calibrating a positioning system using these techniques is a function of the stability of the positioning system being used and the condition of its electronics. According to questionnaire respondents, a repeatability of plus or minus one meter to plus or minus five meters is achieved with this procedure. The base-line method is least susceptible to errors. The accuracy of this technique makes it a very good means of calibration.

Usually due to logistical demands, this method is used only at the beginning and end of a survey or when equipment or component changes are made in the positioning system. This method was at times employed periodically throughout the survey, e.g., monthly. The base-line method was not used for daily calibrations.

Twelve of the 21 questionnaire respondents calibrate using the base-line method. Six of the 12 users employ only this technique to calibrate the Mini Ranger III. The National Ocean Survey, for example, has determined this method to be the only acceptable procedure to calibrate Mini Ranger III [Ref. 13].

An advantage to the base-line method is that it is not restricted by reduced visibility once the distance has been established. Disadvantages include the requirement for a suitable location and a considerable amount of time in the complete removal of the positioning system from the vessel and shore stations. This approach is relatively inflexible in its use over various areas of the survey. The procedure needs to be supplemented with daily calibration checks for the purpose of confirming the validity of base line determined correctors.

2. Electronic Range Finder Method

The electronic range finder method is a variation of the base-line technique. The known distance (vessel to known point) is determined at the time of calibration. This procedure consists of using a hand-held electromagnetic or electro-optical distance measuring device to determine the known distance.

Calibrations are performed from a ship or launch by holding the range finder beside the master receiving antenna and measuring the slant range to a prism or receiving unit located on the shore station antenna. The reverse of this set-up can be done with the range finder being used on the beach and sighting at a prism or receiving unit located on the master receiving antenna. This technique requires shore party support. However, if performed in a range-azimuth survey, this approach can be used effectively, eliminating additional logistic concerns to support calibration.

The vessel can stop and make a calibration at any time during the survey as long as the distance to the shore station is within the limited range of the distance measuring device. This combination probably provides the best calibration data possible when used in conjunction with the base-line method. This technique would provide excellent overall system calibration data. Unfortunately, due to the limited range of some of the more versatile distance measuring devices, some other technique would likely have to be employed to calibrate the positioning system over the maximum range of its intended use. Weather may be an influential factor in that it limits the optical range finder to times of clear visibility. Additionally, there may be a need for someone at the shore site to aim the prism towards the ship or launch unless multiple prisms or reflectors are employed.

The expected accuracy for one optical range finder is plus or minus one-half meter or one-tenth percent of the total range, according to the manufacturer's specifications [Ref. 14]. None of the questionnaire respondents had used this technique, thus comparative accuracy results are not available. One questionnaire respondent suggested this as an alternative method of calibration, although he had no personal experience with it other than having seen it demonstrated [Ref. 15].

3. <u>Base-Line and Base-Line Extension Crossing Method</u>

This method of calibration should not be confused with the base-line calibration procedure. Instead, it involves the calibration of a positioning system when crossing the base-line or base-line extension produced by the geometry of the control stations for each rate. At the time of crossing the base-line, the observed readings of both shore stations are added and compared to the computed base-line distance between the two known locations. By crossing the base-line extension, the differences in observed range readings of the two shore stations are compared with the known base-line distance.

There are equations [Ref. 16] that can be employed to determine the appropriate corrections for each shore station. These formulas utilize the combination of both readings at the base line and base line extension crossing to resolve any error. The base-line extension crossing method can also be used to calibrate hyperbolic systems. For a complete description, see Appendix B.

These methods are not really true forms of calibration as defined by this paper since the positioning system is being compared against itself, thereby not achieving the accuracy that could be obtained by calibrating against an independent measurement or observation. The techniques do provide a validity check on the positioning system and assist the user in determining if the system is operating within its required accuracy limits as well as to reestablish a lane count.

The base-line crossing procedure has been employed by two of the questionnaire respondents. One of the user's procedure required the calibration of at least one shore station rate by an accepted calibration method prior to making crossing comparisons. This results in the determination of which shore station needs to be adjusted if there is a difference in the comparison.

B. POSITION COMPARISON METHODS

The second method of calibration consists of comparing a known position with the observed value obtained from the positioning system at the same location. The method is universal in its application, with either a ranging or hyperbolic positioning system. The known position can be determined by a variety of independent methods.

Position comparison is performed over water, thereby providing the best estimate of all systematic errors at a specific point and time. Multiple comparisons are needed at as many points in the survey area as possible to measure spatial variations.

The position comparison method can be broken down into two types of positions: fixed-point and variable-point positions. A fixed-point position has predetermined lattice coordinates. Direct comparisons can be made with the positioning system's rates at the time of calibration. A variable-point position is a known location that is determined independently at the time of calibration. The variable point coordinates must be computed before a comparison can be made with the positioning system's rates.

1. Fixed-Point Position

The fixed-point position utilizes precomputed electronic lattice coordinates of the known position in comparison with the electronic positioning system's observed values. The fixed-point position is spatially inflexible resulting in calibrations being performed in only a limited area of the survey. Repeated observations are necessary to obtain a good comparison.

There are three general methods of establishing a fixed-point position: visual range-angle method, range-intersection method, and static method.

a. Visual Range-Angle Method

The vessel is maneuvering such that the receiving antenna is placed on a range formed by two control stations of at least third-order accuracy. A predetermined angle is observed with a sextant from the range to a third-order control station to the left or right of the range. The vessel moves at a slow speed, steering so the antenna is on range until the predetermined sextant angle is reached. At that instant, electronic position data are observed and compared with the values precomputed from the sextant angle and range. Several electronic values and positions from predetermined sextant angles along the range can be computed beforehand to allow for calibration at different locations on the range (see Fig. 2).

This method is a variation of the three-point sextant fix with one angle equal to zero. The visual range-angle technique avoids weak fixes which can result from the three-point sextant method due to small observed angles and poor geometry.

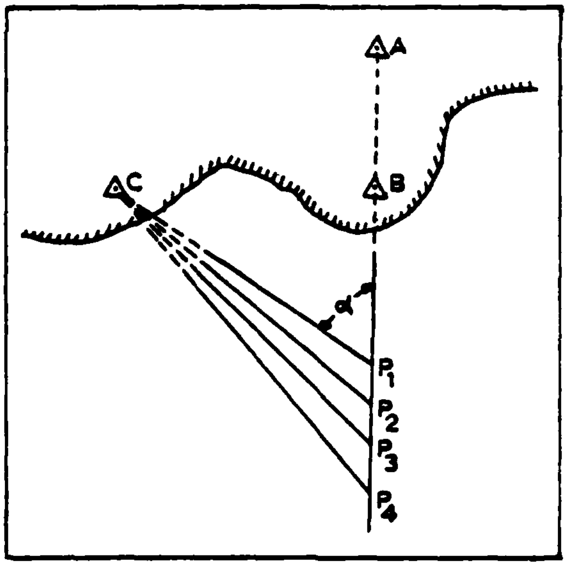

Figure 2. A, B, and C are stations of at least third-order accuracy. The angles α have been predetermined for each point on the range. Positions and electronic values for $P_1 \ldots P_4$ have been computed beforehand [Ref. 17].

To gain the most accuracy on steering the range, the distance between the range objects should be larger than the distance between the vessel and the closest object. One user employing this technique stated: "The ratio of the distance between the range objects (aid to navigation lights) to the distance from the ship to the closest object in the range was approximately seven to one. This high ratio was favorable to acceptable repeatability and accuracy in the method" [Ref. 18]. In all, three of the questionnaire respondents used this method. Their estimated repeatability was on the order of four to six meters, the majority being within two meters.

The accuracy of this procedure is basically the same as that of a three-point sextant fix. Potential sources of error include the ability of the sextant observer, instrument error, geometry of the control, and the ability of the helmsman in keeping the vessel on range at the time of calibration. This latter source probably results in a more significant error than that of the angle measurement. For a sextant observation, the standard deviation is approximately one minute and the expected accuracy of a sextant fix is about one meter per kilometer from the station [Ref. 19].

Using a theodolite (T-2) observer ashore to mark the vessel as it passes the predetermined angles may provide better calibration data than sextant observed angles. However, overall accuracy might not improve since steering the range is potentially the major source of error.

One user reported that maneuvering the vessel on range and observing the angle with a sextant from the receiving antenna can sometimes be a problem. This is especially true if there are strong currents, winds, rough sea conditions, or poor visibility.

b. Range Intersection Method

With the range intersection method, the known position is defined by the intersection of two sets of visual ranges. The vessel steers so that its receiving antenna is on one range while closing the second range at slow speed. When the vessel crosses the second range, electronic position rates are observed and compared with the precomputed lattice coordinates for that point (see Fig. 3).

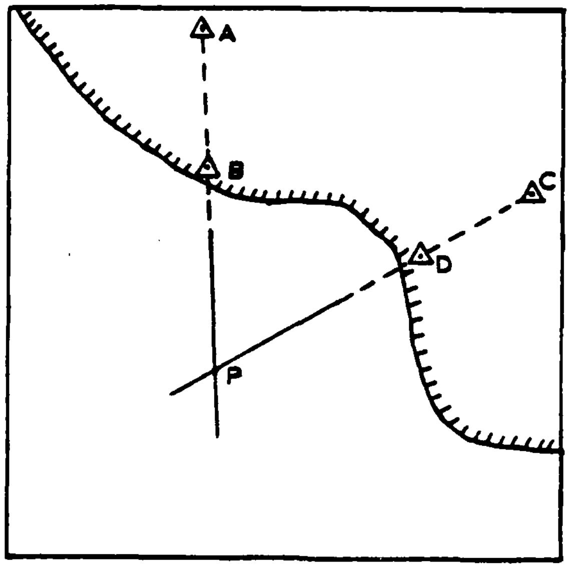

Figure 3. A, B, C, and D are stations of at least third-order accuracy. The position and electronic values for the intersection point P have been precomputed.

Intersection of ranges that are defined by horizontal control stations will have a predictable lattice coordinate value. Ranges can be defined by unpositioned objects, giving flexibility to the location of the calibration, but the position of the intersection of the two ranges must be determined. This can be done by performing a theodolite (T-2) intersection of the ranges' intersection from two third-order control points when the vessel is in position, i.e., in line with both ranges simultaneously. Once the intersection has been determined, the ranges can be used just as if they were defined by positioned objects. The lattice coordinates can also be established by "carrying the rates" to the point based on some other form of calibration.

The accuracy of the technique depends upon the geometry of the azimuth configuration, the means of determining the azimuth of the ranges as well as the position of the intersection point, and the ability of the helmsman to steer the range. The distance ratio for acceptable accuracy in steering the range is the same as with the visual range-angle method. A position determined from the azimuth intersection of two ranges having at least third-order control will have a much higher accuracy than a point determined by theodolite intersection for noncontrolled ranges.

c. Static Method

There are two techniques of calibration employing the static method: (1) coming alongside the object, (2) circling the object ("circle-buoy" method). Both approaches can be utilized to reestablish whole lane count for phase-comparison systems. See Appendix B for methods on locating and establishing stationary objects (includes "circle-buoy" method).

For the first technique, the static known position is defined by the use of a stationary structure such as a piling, beacon, dolphin, or any other accessible object located in the survey area. The vessel, a launch or a small boat, comes alongside the established object, and is positioned such that the receiving antenna is as close as possible to the object (a major weakness of this method). If at all possible the receiving antenna unit should be removed from the vessel and positioned on the object itself in order to increase the achievable accuracy though any offsets may be computed. Comparisons are made between electronic position rates and the predetermined values for that known position.

There are times when the calibration object may modify the positional values that are being checked. One correspondent wrote that, "HFP Launch 1257 has ceased using the fixed point calibration because it was apparent that the fixed point calibration structure was modifying the Raydist signal" [Ref. 20].

From the results of the questionnaire, it is apparent that the static method is the most preferred calibration technique (13 correspondents), especially for comparison checks performed during the survey. It is also probably the most abused method since many times calibrations are made when not on station, with offsets being ignored. One respondent wrote that this procedure was always used unless impracticable or impossible since it yields the most accurate and cost effective results when available [Ref. 21]. This technique may be the fastest one to employ if the distance to the work area is reasonable and the least susceptible to errors. Its superior accuracy makes it worth the additional time and effort to position the stationary object with third-order control methods. A minimum accuracy of one part in 10,000 can be achieved with third-order methods. Fixed points in the survey area allow for calibration at any time it is necessary providing much more repeatability than that obtained from the three-point sextant method [Ref. 22]. The user's repeatability was on the order of one to four meters. Not being able to position the receiving antenna on the object, as well as sea conditions when trying to maneuver into position, are some of the factors that would affect the repeatability of the positioning system during calibration.

Finally, this method is not restricted by reduced visibility; however, it requires a suitable object or location which may present logistic difficulties. Also, maneuvering a launch in heavy seas or high currents when coming alongside the object can be hazardous. In most cases it is too cumbersome and dangerous for larger vessels.

2. Variable-Point Position

With the variable-point position scheme, the known control point is determined by an independent method at the time of calibration. The procedure requires computer capabilities or graphics to determine the lattice coordinates of the known point for comparison with the observed values of the position system. The variable-point position approach is spatially flexible, providing calibrations in an unlimited number of locations in the survey area. To obtain the best accuracy, geodetic control points of at least third-order accuracy should be used for determining the known position.

a. Sextant Calibration Method

The method involves the use of three sextant observers and redundant observation. While the vessel is close enough to shore to enable the observation of visual horizontal control signals, a three-point horizontal sextant fix and check angle are observed simultaneously to obtain the position of the receiving antenna. This technique provides a self-checking feature since each angle is independent of the others. The known position is in effect determined by two sets of angles simultaneously, thus providing a check on itself. Electronic rates of the positioning system are observed simultaneously, recorded and compared to the equivalent values of the fix obtained from the observed angles.

The control stations should have a good geometrical configuration for the best results. Strong fixes will depend upon the choice of proper signal geometry. Angles of less than 30 degrees should be avoided whenever possible. This method requires the angle observers to be as close together as possible and as close as possible to the receiving antenna when obtaining a fix.

The accuracy and repeatability achieved with this method of calibration varies from one to ten meters. This technique is very susceptible to errors. A main source of error is the human factor such as eccentricity due to the three sextant observers not all standing where the receiving antenna is located when obtaining a fix (a physical impossibility). Other human factors that result in errors are due to observers not observing the angle simultaneously, observer and objects not lying in the same plane, and misidentification of a signal. Other sources of error result from adjustable and nonadjustable errors (instrument error) inherent in the sextant [Ref. 23].

The sextant method is restricted by reduced visibility, a limited range of approximately five kilometers, and the amount of proper control available. The manpower requirement is high, but a minimum investment in equipment is required.

Thirteen correspondents indicated using sextant calibration. One respondent ranked it as the most preferred procedure, since it has been used for so many years. Despite its inherent inaccuracies it provides a good system to fall back on when other methods are not available, and, under some specialized circumstances, may be the most desirable approach [Ref. 18]. The sextant method for calibrating microwave systems was not recommended by one correspondent based on his conviction that Mini Ranger is inherently more accurate [Ref. 21].

b. Electronic Range-Azimuth Method

The electronic range-azimuth method involves the determination of the known position by observation of an azimuth, with a theodolite, and an electronic range to the receiving antenna on the vessel. A theodolite and ranging instrument are positioned over the same geodetic control station. The theodolite uses another control station of equivalent or better accuracy for its initial azimuth. A prism or receiving unit is mounted (or held as close as possible) to the master antenna on the vessel to transmit back the pulse light or signal received from the ranging instrument. When calibrating, the receiving antenna on the vessel is simultaneously sighted on by the theodolite, a range reading made, and the positioning system's rates observed and recorded.

The procedure requires the use of a surveying theodolite (T-2) and a surveying ranging instrument such as the Electronic Range Finder [Ref. 14] or the Tellurometer CA1000-D EDM [Ref. 24]. An electronic (infra-red) theodolite which combines the angle and the electronic distance measuring capabilities into a single compact unit would provide an ideal approach [Ref. 25].

The accuracy of a ranging instrument, providing the target is stationary, is on the order of plus or minus one-half meter or one-tenth percent of the total range for the Electronic Range Finder, and plus or minus two feet at a range up to 10 miles for the dynamic use of the CA1000-D. An accuracy of plus or minus five millimeters plus five millimeters/kilometer is obtainable for an electronic theodolite ranging component. The accuracy of a theodolite azimuth observation, taken as one-half minute of arc, results in approximately seven-tenths of a meter displacement of the vessel at five kilometers.

Sources of error that affect the accuracy are the ability of the theodolite observer, proper leveling and adjustment of the theodolite, having both the theodolite and range finder centered over the control station, and the misidentification of the control stations both occupied and observed.

This technique is very effective in areas of limited control. When a range-azimuth survey is being performed using a microwave positioning system and a theodolite, for example, this means of calibration may be utilized most effectively. A calibration, employing one of the previously mentioned EDM instruments, can be obtained at any time during the survey, such as at the end of a survey line, resulting in little time lost between breaking the survey operations, calibrating, and returning to the survey work.

The method may be limited by the maximum effective range of the distance measuring unit being used. The range for the electronic theodolite is five kilometers, for the Electronic Range Finder up to seven kilometers, and up to 30 kilometers for the CA1000-D. Note also that with increasing range the azimuth of the theodolite degrades rapidly.

None of the questionnaire respondents indicated using this type of calibration, although one respondent did suggest it as an alternative method.

c. Theodolite (Azimuth) Intersection Method

When using this technique, the known position is determined by the intersecting azimuth of two surveying theodolites (T-2), both of which are positioned over horizontal control stations. The control stations need not be intervisible, but the azimuth or initial used from each station must be of equivalent or better accuracy. The receiving antenna on the vessel is positioned by the intersection of the two azimuths from the theodolites while simultaneously obtaining the positioning system's rates.

The accuracy of this technique depends upon the geometry of the azimuth configuration; the same conditions that affect the three-point sextant method. A one-half minute angular error in the theodolite observation equates to a position error of approximately one-and-a-half meters at ten kilometers from the stations.

This method is both fast and accurate once shore sites have been established. The calibration accuracy obtainable is better than the accuracy of the three-point sextant procedure. Nine questionnaire respondents indicated that they used this technique for calibrating. These calibrations can be quickly computed with small calculators having geodetic programs.

d. Three-Range Microwave Method

With this approach the known position for comparison is determined by the observation of three range rates from a microwave positioning system while simultaneously observing the rates of the system being calibrated. With three ranges, the known position is in effect determined by three pairs of ranges simultaneously. This also provides a check on the microwave system itself.

This technique is used to calibrate medium range phase comparison systems only. A convenient means of on-site comparison is to calibrate both positioning systems simultaneously by using the theodolite intersection method. To provide the best accuracy, the microwave system should be calibrated by the base-line method. In general, the accuracy of this method depends on the repeatability of the microwave system and the technique used to calibrate it.

The main advantage to this method is that a phase comparison system can be calibrated at any time and in any weather. The major disadvantage is the requirement for expensive equipment and extensive logistic support for maintaining the microwave system.

Five questionnaire respondents use this as a means for calibrating phase comparison systems. It was found that on the average, weekly calibrations of the microwave system are sufficient. This was determined from watching the inverse between fix and the check fix [Ref. 26]. Due to the accuracy and versatility of this procedure, having to calibrate a medium range phase-comparison system with the three-point sextant or theodolite intersection method would be eliminated in most circumstances [Ref. 21].

e. Three or Four-Signal Calibration Transfer Method

An electronic positioning system that can receive and display rates from three or four stations simultaneously is employed. The pair of shore stations that is used for position control initially are calibrated in the best available manner. When the vessel reaches the area where all four signals are received without interference, and just before leaving the usable work area of the initial pair that have been calibrated, the vessel will determine the exact position rates of the second pair. The second pair will be corrected at this time and can then be used for position control. This pair will be calibrated using the best available method when the vessel reaches a suitable area to verify the position values and provide correctors as required. When only three signals are received simultaneously, the vessel calibrates the third rate before switching from one of the initial pair of stations in order to change the control.

The approach outlined is not a true form of calibration as defined by this paper. Just as in the base-line crossing technique, the positioning system is being compared against itself.

The accuracy of this method depends upon the accuracy of the technique used to calibrate the initial pair of shore stations. Repeatability of the positioning system also affects the accuracy.

If the vessel is able to receive all four rates simultaneously, all can be calibrated at one time. With redundant observations, if the reliability of any fix obtained from the two stations being used is in question, an inverse distance from the position obtained can be computed and any problem identified.

This method eliminates the need of transit time, from the survey area and back, to recalibrate when switching from one positioning net configuration to another. It is a useful alternative when there is limited control for calibrating certain net configurations in the survey area.

Only two questionnaire respondents indicated using this technique and then only with a phase comparison system that could receive at least three position rates simultaneously.

C. AUTO CALIBRATION METHODS

The auto calibration technique calibrates the electronic positioning system against itself by using redundant lop information which in turn is adjusted to obtain the most likely position. Utilizing redundant lops, a determination as to whether or not there are systematic (fixed or variable) errors in the positioning system can be made at any time. Variations in the system, both spatially and temporally, can be determined. This capability must be designed into the system, requiring special and costly equipment. It can be used with either ranging or hyperbolic systems and permits great flexibility throughout the survey area.

1. <u>Raydist Director System</u>

The Raydist Director System incorporates the principles of auto calibration by interrogating simultaneously and continuously four independent ranges (shore stations). The vessel passes in any direction in the area of the survey, collecting position data from all control stations. A complex set of equations dealing with changes in range to the base station is used to derive only one fit for all four position rates. The system performs a statistical analysis, i.e., adjust rates for best fit by least squares for each station, thus providing automatic error detection and correction [Ref. 27].

Complete and unambiguous lane identification, including fractional values, are provided. This allows for reestablishment of the exact position within minutes after losing lane count due to a power failure, equipment failure, atmospheric phenomena, or other causes, by processing redundant data supplied by the four shore stations using the mathematical model in the system.

This system results in reduced operating time and costs, as well as increased accuracy. Positioning systems of this type improve the absolute accuracy (predictability) of an operation to a standard deviation of one-and-a-half meters [Ref. 27].

None of the questionnaire respondents indicated using this system. "The Yugoslavian Naval Hydrographic Office bought the first marine model" of the Raydist Director System [Ref. 28].

2. Alternative Application of Least Squares to Redundant Observations

In general, the least squares method provides a mathematical procedure by which the most probable values of acquired quantities are obtained from a set of observations. The most probable value is the value of an observed quantity that has the highest probability. The observed quantities are said to be adjusted after this technique and the necessary corrections have been applied. For a set of observations, the fundamental condition in the least squares method is that the sum of the square of the residuals is minimized, a residual being the difference between an observed value of a quantity and the arithmetic mean value of that quantity obtained from a number of observations. In order to use this procedure redundant observations are required. This procedure can be applied to other methods where redundant information is available: (1) the three-range microwave method, or (2) the three or four-signal calibration transfer method.

In the least squares adjustment method, the observed quantities are related to the desired unknown quantities through mathematical functions called observation equations. For each measurement, there is one observation equation written. The observations are assumed to be independent of each other. When obtaining a unique position solution there would normally be two equations and two unknowns. By obtaining redundant observations there will be more observation equations than unknowns. The most probable values of the unknowns can be determined, thus providing a means of calibration. The observation equations can be either linear or higher-order functions. For an in-depth discussion on this application and the mathematics of least squares, see Kaplan, 1980 [Ref. 29].

By using an electronic positioning system that can receive at least three position rates continuously and simultaneously, the least squares adjustment method can be used to compute the coordinates at any particular position in the survey area. Position rates from three shore stations are obtained while the vessel is performing normal survey operations. The observation equation can be employed, using matrix notation and successive observation information, for a best fit of each position as well as the detection of errors in any of the position rates. The technique could reduce operating time and costs, as well as increase accuracy, as compared with other methods of offshore calibration.

Least squares applies the same procedure as built into the Raydist Director System with processing done on line. Using least squares to calibrate, computer software is needed to make the comparisons off line.

VI. CONCLUSION

The calibration of electronic positioning systems consists of a variety of methods which in most cases are time consuming and expensive, but necessary to ensure the accuracy of the hydrographic data. By calibrating these types of systems over various regions of the survey, and at different times, the systematic (fixed and variable) errors can be estimated and compensated for in the positioning data.

When deciding on the best possible calibration technique, several considerations must be taken into account. The method selected will depend on the type of positioning system being used, the accuracy requirements for the scale of the survey, and the ability to establish an appropriate calibration site (availability of adequate control, logistics, location requirements).

Ideally, two types of calibration should be performed: (1) stationary calibration using the base-line or static method where redundant observations can be made, and (2) dynamic calibration throughout the survey area.

The most accurate stationary technique for calibrating any range measurement system, whether pulse-time or phase-comparison, is the base-line method; unfortunately, it is also the most time consuming and inflexible in its application over the survey area. It is important to note that microwave ranging systems can use this procedure over either a land or water path. Systems using radio frequencies must be calibrated over water due to the extreme variability of propagation velocity between a land and water path. When calibrating the ranging system in the survey area, the static method (a stationary comparison), electronic range finder, azimuth (T-2) intersection, and electronic range-azimuth methods provide the best accuracy. The latter three techniques (dynamic comparisons) are, within their range limitations, the most flexible.

Hyperbolic positioning systems can not be calibrated by the base-line technique or any other method where a single range is being employed for the comparison. The static method provides the most accurate stationary calibration and is one of the least time consuming techniques for this type of system. It is not flexible in providing calibrations over various areas of the survey. The techniques providing the most flexibility over the survey area and at the same time having very good accuracy for a hyperbolic system are the azimuth (T-2) intersection and the electronic range-azimuth methods (dynamic calibrations).

When a phase-comparison system is being utilized, calibration serves two purposes: (1) check or reestablish whole lane count, (2) estimate systematic errors. Crossing a base line or rate transfers are good for the first but not for the second purpose.

An auto calibration system, such as Raydist Director System, which includes the necessary hardware and software features, provides the best accuracy and versatility in its use throughout the survey area for a positioning system. The principles of this system could be incorporated into any type of electronic positioning system, but the cost/benefit concerns would be a major consideration in its implementation.

By being able to obtain redundant observations, the application of the method of least square adjustments can be used to calibrate any type of positioning system, both spatially and temporally, during the survey. In most cases of particular concern, the appropriate observation equations and redundant data can be entered into a ship or launch-board minicomputer, the best fit for a position can be made, and appropriate corrections determined. It would be advantageous to have this method of calibration developed further since it offers the possibility of calibrating a system in real time. The main limitation is the need of redundant observations.

Depending on the particular situation and an operator's ingenuity, other methods can be devised to calibrate or check the positioning system.

APPENDIX A

RESEARCH QUESTIONNAIRE

The following questionnaire was sent to various users and manufacturers of electronic positioning systems:

I am in the process of working on a research project in the Oceanography/Hydrography Curriculum at the Naval Postgraduate School, Monterey, California. The research will involve the evaluation of calibration methods for Hydrographic Control Systems.

Since there are probably as many calibration methods as there are Hydrographic Control Systems, an effort is being made to catalogue the various calibration methods that are being used for each type of system available. In addition, an evaluation will be made as to which method may be best suited for certain conditions and accuracy requirements.

To help me obtain the information needed to accomplish this project, I would appreciate it if you could answer the questions on the following page with respect to your particular systems.

In order to get the data and use it for this research, your immediate attention to this matter is appreciated. I would like to have this information no later than January 1, 1980.

Please provide your name and telephone number so I may contact you if any questions regarding your answers should arise.

If you would like a copy of the research results, I would be glad to send you one. _____ YES _____ No

Please submit answers to:

Lt. Kenneth W. Perrin, NOAA
SMC Box 1710 NPS
Monterey, CA 93940
Telephone: 408-646-3131

Thank you.

1) What type of Hydrographic Control System(s) do you use?

2) What method of calibration do you use for each system? Describe. (If more than one method is used for the same system, please explain what the conditions are for using a particular method).

3) What type of repeatability (accuracy error) do you get from one calibration to the next?

The questionnaire was sent to the following users and manufacturers of electronic position systems:

USERS:

Pacific Marine Center, NOAA
1801 Fairview Ave., East
Seattle, Washington 98102

The following at the above address:

The Commanding Officer of the NOAA Ships:

*Fairweather

*Rainier

*Davidson

*McArthur

*Surveyor

*Miller Freeman

*LCDR. David MacFarland, CPM 130

*LCDR. Pamela Chelgren, CPM 3

*LCDR. Dirk Taylor, Chief, Pacific Hydrographic Party

Atlantic Marine Center, NOAA
439 W. York St.
Norfolk, Virginia 23510

The following at the above address:

The Commanding Officer of the NOAA Ships:

*Mt. Mitchell

Whiting

Peirce

Rude & Heck

Ferrel

*George B. Kelez

*LCDR. Thomas Richards, Chief, Hydrographic Surveys Branch

*LCDR. David Yeager, CAM 1

*Mr. Jim Shea, CAM 102

*Chief, Electronic Engineering Department, CAM 6

*Canadian Hydrographic Service
615 Booth Street
Ottawa, Ontario K1A 0E6

*Atlantic Region
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

Laurentean Region
Ocean & Aquatic Sciences
P.O. Box 75500
Cap Diamant
Quebec, Quebec G1K 7X7

*Central Region
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario L7R 4A6

*The Commanding Officer
USNS Chauvenet
OCUNIT
FPO, San Francisco, California 99601

*U.S. Army Engineers District
Hydrographic Surveys Division
P.O. Box 1027
Detroit, Michigan 48231

MANUFACTURERS:

*Decca Survey Systems,Inc.
Houston, Texas

Del Norte Technology,Inc.
P.O. Box 696
Euless, Texas 76039

Motorola Government Electronic Division
8201 E. McDowell Road
Scottsdale, Arizona 85252

Teledyne Hastings-Raydist
P.O. Box 1275
Hampton, Virginia 23661

*Cubic Western Data
P.O. Box 80787
San Diego, California 92138

*Asterisk indicates response received.

QUESTIONNAIRE RESPONSE

Number of questionnaires sent:	30
Number of responses received:	21
Response rate:	70%

Number of responses for each calibration method:

BASE-LINE METHOD	12
ELECTRONIC RANGE FINDER METHOD	1
SEXTANT CALIBRATION METHOD	13
ELECTRONIC RANGE-AZIMUTH METHOD	1
VISUAL RANGE-ANGLE METHOD	3
THEODOLITE (AZIMUTH) INTERSECTION METHOD	9
RANGE INTERSECTION METHOD	1
THREE-RANGE MICROWAVE METHOD	5
THREE OR FOUR-SIGNAL CALIBRATION TRANSFER METHOD	2
BASE-LINE AND BASE-LINE EXTENSION CROSSING METHOD	2
STATIC METHOD	13

Request rate from responses for copies of the research results------------------------- 100%

APPENDIX B

BASE-LINE AND BASE-LINE EXTENSION CROSSING METHOD

For positioning systems which operate in the range measurement mode, the following procedure and equations can be used to determine corrections for each control station.

B = base-line length

RC = required correction (red)

GC = required correction (green)

CASE I: Indicators calibrated by cutting base line and the red extension (Fig. B-1) [Ref. 16]

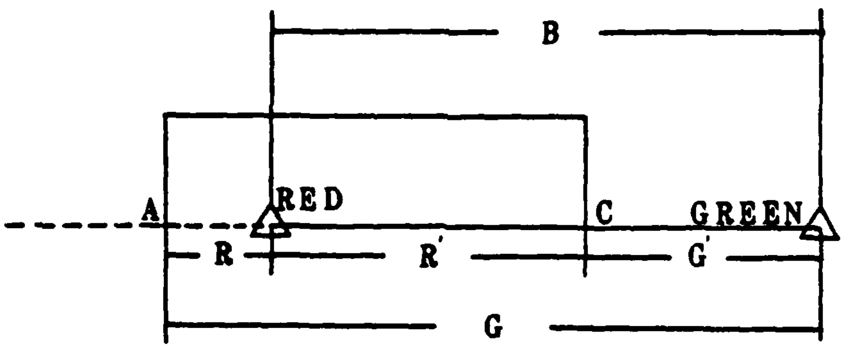

Figure B-1

At point A, read indicators upon crossing red base-line extension to obtain R and G.

At point C, read indicators upon crossing base line to obtain R' and G'.

$$RC = \frac{(G - G') - (R + R')}{2}$$

$$GC = \frac{(R - R') - (G + G') + 2B}{2}$$

<u>CASE II</u>: <u>Indicators calibrated by cutting base line and the green extension</u> (Fig. B-2) [Ref. 16]

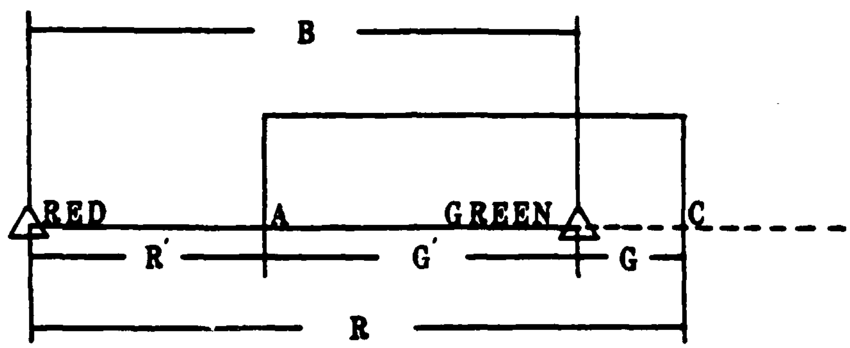

Figure B-2

At point A, read indicators upon crossing base line to obtain R' and G'.

At point C, read indicators upon crossing green base-line extension to obtain R and G.

$$RC = \frac{(G - G') - (R + R') + 2B}{2}$$

$$GC = \frac{(R - R') - (G + G')}{2}$$

For positioning systems which operate in the hyperbolic measurement mode, the base-line extension crossing procedure can be used to determine corrections for each control station (see Fig. B-3) [Ref. 16].

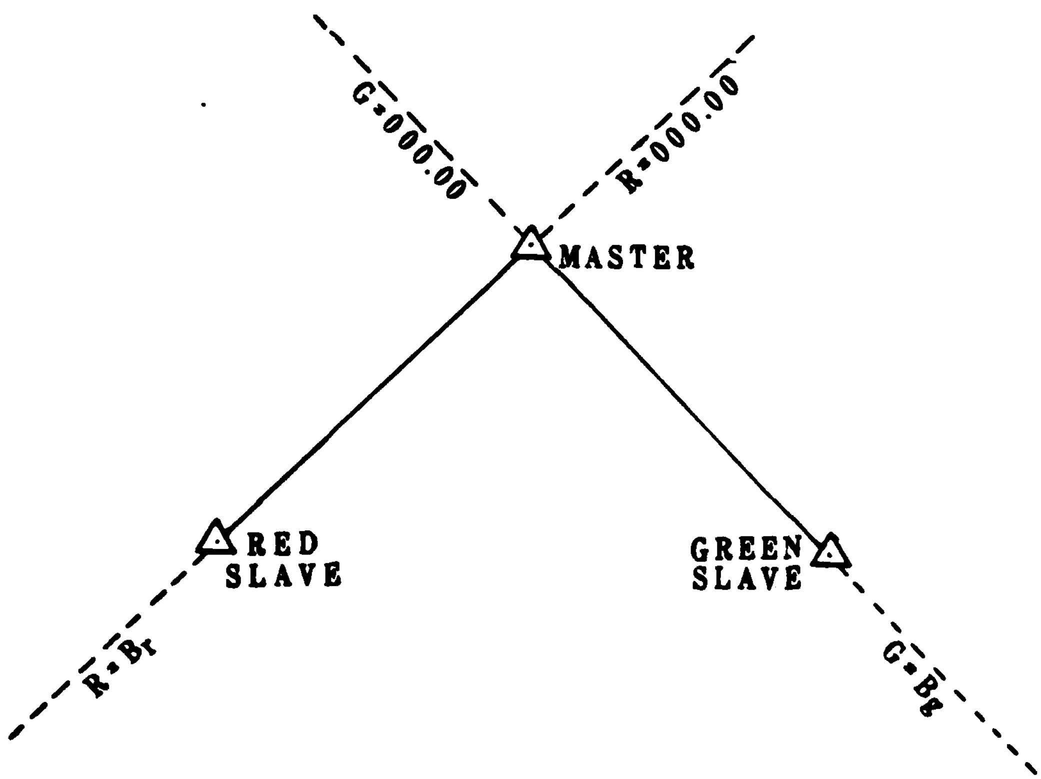

Figure B-3

When a base line or a base-line extension (dash lines) is crossed by a vessel, one set of dials will reverse direction. When crossing one of the inner base-line extensions (the base line extensions joining the center station), the minimum value of the net (zero) will be received. When a vessel crosses one of the outer base-line extensions (the base-line extension joining either the red or green station), the maximum red or green value of the net (Br or Bg) will be received.

Calibration of the red or green station may be obtained by either crossing the inner or outer base-line extension. When the dial reverses, it should be reading either zero or the maximum value (Br or Bg) of the system. If the above do not hold true, correct the red dial to the desired value.

The base-line extension should be crossed at approximately the same point in both directions, obtaining two minimum readings. Best results in calibration on base-line extension should be experienced at distances of five to ten nautical miles from the near antenna. When using a helicopter to calibrate the system, at a distance of five miles from the antenna, it is desirable that 100 feet be considered maximum altitude. Heights up to 500 feet are permissible at a distance of 10 miles with 100 feet altitude being minimum.

Other guidelines to follow to ensure better accuracy of calibration are: (1) the crossing point should not be within 1000 feet of a land-water boundary, (2) the crossing point should not be within 1000 feet of buildings, power lines, railroads, or other structures which may produce local induction and re-radiation effects, and (3) there should be no obstacles between the near antenna and aircraft of sufficient height so as to block the direct signal.

Base line and base-line extensions totally over water provide the best calibration accuracy, while all-land paths produce the largest errors. Water-land path combinations result in varying accuracies, with the following serving as a guide: (1) with the base line over water and base-line extension over land, the accuracy of calibration should approach that for all-water paths, (2) with the base line over land and the base-line extension over water, the accuracy should be slightly better than for all-land propagation paths, also (3) with broken land and broken water paths, the accuracy can range from that of an all-water path to that of an all-land path depending upon the ratio of the water path to that of the land path and the order of arrangement. It may be generally stated that for a one-to-one water-to-land ratio, the resulting accuracy will vary from the average of water-land accuracy to that of all land [Ref. 16].

APPENDIX C

LOCATING AND ESTABLISHING STATIONARY OBJECTS

If there are no objects with known positions in the survey area already available, several procedures can be used to either locate an existing object or to establish a calibration fix point. The techniques used are the same as in some of the various calibration methods. The object can be located either by theodolite (T-2) intersection cuts, a three-point horizontal sextant fix with a check angle, or by electronic range-azimuth positioning. Various existing objects that can be located for calibration purposes by these methods are the end of piers, a designated point along a dock, breakwater, or bulkhead, an exposed rock in the survey area, or a buoy.

When a vessel is using a medium range phase-comparison system in a survey area that is a considerable distance off-shore, a buoy in that survey area should be established for a check on the whole lane count of the system. In order to locate this buoy, the vessel must first obtain a good calibration near shore by the best available method. On the way back to the survey area careful watch on the positioning system must be maintained to be assured of no lane losses. Once in the survey area, the vessel can then position the buoy by coming alongside of it and obtaining several observations, averaging the ones in good agreement, and computing the position and lane values for the buoy. The vessel can then use the buoy for redetermining and checking the whole lane count if necessary.

In the circumstance that the vessel is unable to come al ;side the buoy, the "circle-buoy" method can be used if the line-of-position arcs are of larger radius. A position on the buoy can be determined by passing close to the buoy while holding one rate steady with the other rate changing. The electronic position values are observed and recorded when the buoy is abeam. The procedure is repeated while the second rate is held steady with the first rate changing. This should continue until the buoy has been circled completely. The entire procedure should be done several times, maintaining the same distance from the buoy each time. An average of the position values will give the position of the buoy.

By computing or scaling azimuths for the line-of-position where the buoy is located, the vessel can check the whole lane count at any time. While the vessel circles the buoy, the bearing of the buoy is continuously observed with a pelorus. At the time that the bearing of the buoy is the same as the azimuth of a line-of-position for a particular arc, the lane count for that arc on the vessel is the same as that of the buoy (see Fig. C-1). In circling the buoy in such a manner, the vessel will cross each arc twice. This procedure is repeated until there is a satisfactory agreement of the correctors. Once the correctors are applied, another circle of the buoy should be made for verification. "If the vessel is not equipped with a gyroscope repeater and pelorus from which accurate bearings can be observed, whole lane values may be determined by estimating the bearing from the vessel to the buoy and by obtaining the distance by a range finder or depression angle from the horizon" [Ref. 17].

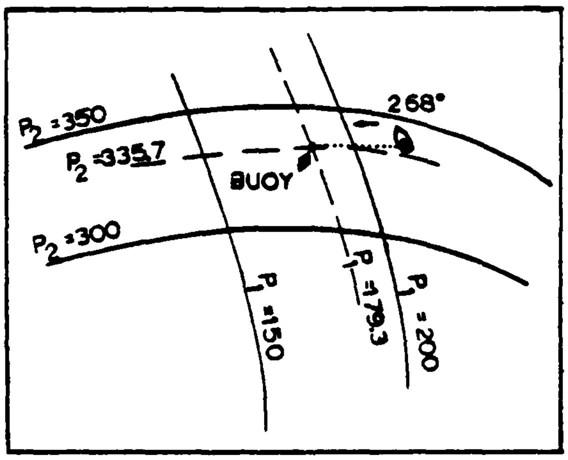

Figure C-1. When the observed bearing of the buoy from the vessel is 268 degrees, the whole lane value for the line-of-position P_2 is 335 lanes [Ref. 17].

If there is a lighthouse tower or an offshore rig in the survey area, the position of which is accurately known, then an exact lane count can be determined by the same circling method. Since the structure is stationary, the partial lane count may be obtained if the procedure is repeated enough times to get a satisfactory agreement among the correctors.

For circling offshore rigs there are two methods, depending on the location of the known position on the rig. If the point has been located in the center of the rig, then an eight-point fix can be made on the rig by circling at an equal distance and fixing the position, i.e., reading the position rates (see Fig. C-2). A four-point run is made when the known coordinate for the rig is on one of the four corners. Four rate readings are made while circling at an equal distance around the known position on the rig (see Fig. C-3). By computing the mean of the readings, the rate reading for the control position on the rig can be determined and compared to the actual rates [Ref. 30].

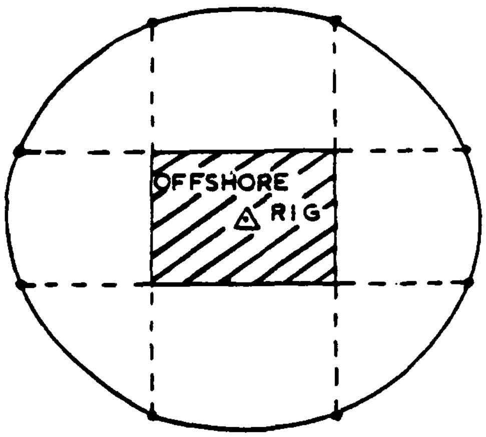

Figure C-2. Eight-point calibration run [Ref. 30]

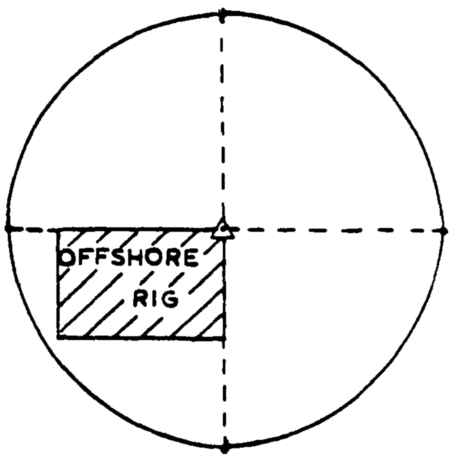

Figure C-3. Four-point calibration run [Ref. 30]

A three-point mooring system can be used to establish a buoy so as to ensure little drift from its determined position. The material used for the construction of this mooring consists of one-inch diameter Manila line, three 100-pound danfort anchors, a metal tie-ring, and a small buoy. The Manila line is used because it will shrink four to five percent when wet, thus tightening up the mooring once in place. The ratio between the depth of water in which the buoy will be moored and the length of line between the anchors' tie point should be approximately one to ten to ensure a good stable mooring. For example, a buoy moored in 30 feet of water will require 300 feet of Manila line for each anchor line (see Fig. C-4a). The angle between the anchor lines should be approximately 120 degrees to provide an equal distribution around the buoy (see Fig. C-4b). A tagline is tied to the metal tie-ring and the buoy is attached to the other end. The length of the tagline is not important but it should be long enough to prevent the buoy from being submerged at the highest tidal level. The three-point buoy mooring system is fairly stable with only about a one-and-a-half to two meter displacement in a three-knot current [Ref. 31].

Once the buoy is properly moored, a position on the buoy is determined by one of the previously mentioned techniques. Whenever a calibration is needed the vessel can come alongside, pick up the buoy putting tension on the tagline to ensure that the vessel is over the buoy mooring, and perform a static calibration. This mooring may be stable enough to provide partial lane determination when calibrating a phase comparison system using the "circle-buoy" method.

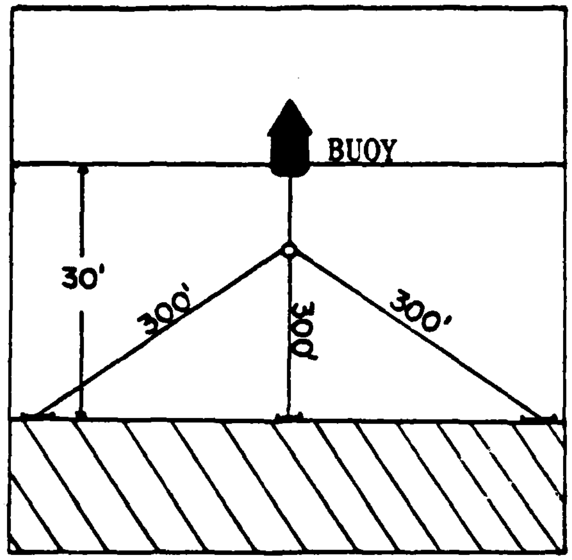

Figure C-4a. Three-point buoy mooring system (side view)

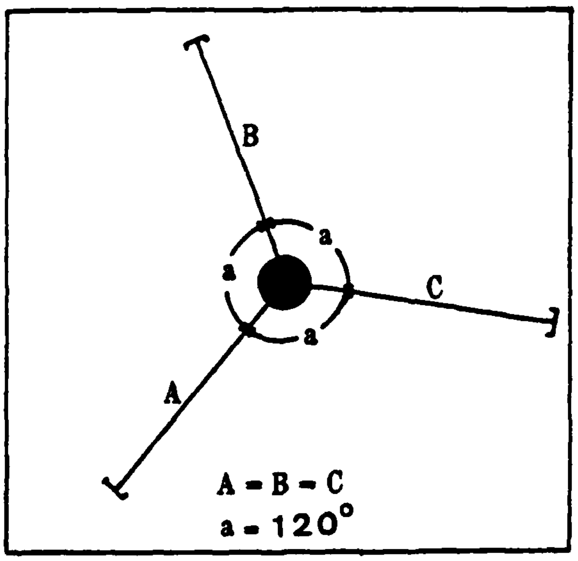

Figure C-4b. Three-point buoy mooring system (top view)

Another buoy mooring technique, though not as good as a three-point mooring, is to use railroad wheels as the anchor and a single one-inch diameter Manila line of minimum scope to secure the buoy to the anchor so that the buoy floats just at the surface during the lowest tide. Attached to the top of the buoy will be another line with a series of small floats (plastic bottles) attached along the line. This line should be long enough to account for the highest tidal level (see Fig. C-5). Once the buoy is moored, the vessel can come alongside, pick up the series of small floats, thus applying tension on the line to ensure that the vessel is over the mooring, and then determine the position of the mooring by the best available method.

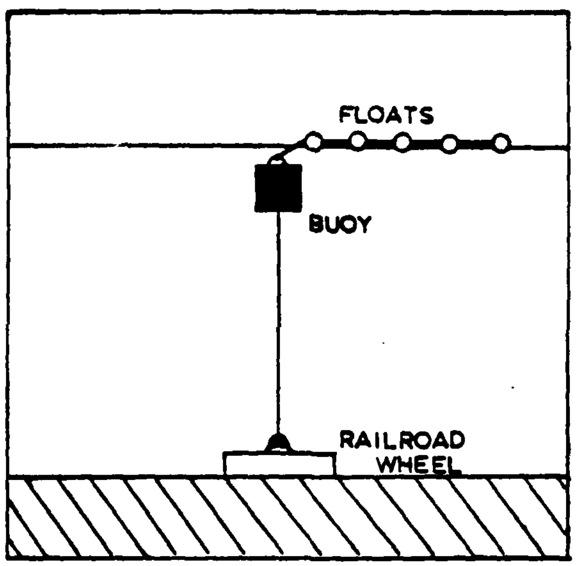

Figure C-5. Buoy mooring, low tide.

Another approach is to come alongside the buoy on the up current side and perpendicular to the string of floats, making observations when the antenna is lined up with the string of floats. The buoy can then be used to calibrate the positioning system at any time that it is necessary.

In both cases, the buoys should be painted international orange to increase the chance of being seen by other vessels. If possible, a radar reflector should also be attached to the buoy to aid its detection, especially at night.

A variation of the static method of calibration, as mentioned by one of the questionnaire respondents, is the bridle method [Ref. 18]. With this method the launch positions itself by attachment to a bridle which in turn is attached to a stationary object such as a bulkhead, pier, or dock. While the launch is backing down, keeping equal tension on both sides of the bridle, a calibration of the positioning system can be performed once that position has been determined by a method such as a theodolite (T-2) intersection.

APPENDIX D

TABLE I

SUMMARY OF CALIBRATION METHODS

Calibration Methods	Positioning System Types that can be Calibrated	Computer or Graphics Capabilities Needed during Calibration	Estimated Accuracy of Calibration Method	Calibration Restrictions-Flexibility in use over Survey Area	Extra Logistics Equipment & Personnel Requirements during Calibration
Base Line	PT,R/R* CP,R/R	None (1)	(3) 1 part in 10,000 ±1 millimeter to ±5 centimeters	Nonflexible Limited to on or near shore	For Measured Base Line -- EDM instrument and Personnel on Shore
Electronic Range Finder	PT,R/R CP,R/R	None	(4) ± 1/2 meter or 0.1% of total range.	Visibility, (13) Limited range near shore, Flexible.	EDM instrument and Personnel on shore.
Base-Line & Base-Line Extension Crossing	PT,R/R,H CP,R/R,H	None (1)	(11) ±1 to ±20 meters	Nonflexible Limited to on or near shore.	Depends on technique used. (usually none)
Visual-Range Angle	PT,R/R,H CP,R/R,H	None (2)	(5) 1 meter per 1 kilometer	Visibility, (14) Nonflexible - Limited to near shore.	One Sextant and Range -- One Observer.
Range Intersection	PT,R/R,H CP,R/R,H	None (2)	(6) 1 centimeter to 2 meters	Visibility, (14) Nonflexible - Limited to near shore.	Two Ranges
Static	PT,R/R,H CP,R/R,H	None (2)	(7) 1 part in 10,000 1 millimeter to 5 centimeters	(14) Nonflexible	Stationary Point or Buoy.

*See key: Numbers in ( ) are notes, see following page after tables.

TABLE I (Continued)

Summary of Calibration Methods

Sextant (three point fix with check angle)	PT,R/R,H* CP,R/R,H	Yes	(5) 1 meter per 1 kilometer	Visibility (15) Flexible - near shore.	Three Sextants, Adequate signal control, three observers.
Electronic Range-Azimuth	PT,R/R,H CP,R/R,H	Yes	(8) 1 meter	Visibility (13) Flexible - Limited range - to near shore.	One theodolite/ranging instrument, Personnel on shore.
Azimuth (T-2) Intersection	PT,R/R,H CP,R/R,H	Yes	(9) 1 to 2 meters	Visibility, Flexible - Limited range - to near shore.	Two theodolites and Personnel on shore.
Three-Range Microwave	CP,R/R,H	Yes	(10) 3 to 5 meters	Flexible over total survey area.	Monitoring and Maintenance of Additional positioning system.
Three or Four Signal Calibration Transfer	PT,R/R,H	Yes	(11) 3 to 20 meters	Flexible over total survey area.	Depends on method of initial calibration.
Raydist (12) Director System	CP,R/R,H	Yes	1-1/2 meters	Flexible over total survey area.	Four remote shore stations
Alternate Application of Least Squares to Redundant Observations	PT,R/R,H CP,R/R,H	Yes	(16)	Flexible over total survey area	Three remote shore stations

*See Key, Numbers in ( ) are notes, see following page.

KEY AND NOTES FOR TABLE I

Key for Positioning Systems:

PT -- Pulse Signal-Time Elapsed System.

CP -- Continuous Wave-Phase Comparison System.

R/R -- Range-Range Measurement.

H -- Hyperbolic Measurement.

Notes:

1. Precomputation of geodetic inverse distance.
2. Position and rates precomputed.
3. Geodetic inverse distance 1 part in 10,000, third-order control. EDM measurement, ±1 millimeter to ±5 centimeters [Ref. 12].
4. For a specific instrument [Ref. 14].
5. From Ingham [Ref. 19].
6. For ranges consisting of third-order geodetic accuracy. Non-controlled ranges -- intersection point determined by Azimuth (T-2) intersection method 1 to 2 meters.
7. For points located by geodetic third-order accuracy methods. Accuracy variable depending on method used to locate point.
8. Accuracy dependent on accuracy of instrument used.
9. Degree of accuracy dependent on geometrical configuration, distance between stations, distance from station and angular resolution of instrument observation.
10. Depends on accuracy of microwave system.
11. Depends on accuracy of positioning system being used.
12. For a specific positioning system [Ref. 27].

13. Depends on range of ranging instrument as to maximum offshore observation.

14. Calibration in only a particular part of survey area.

15. Sextant observation up to 5 kilometers from stations (Ref. 32].

16. Depends on the number of iterations performed. Accurate to within the resolution of the system being used.

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